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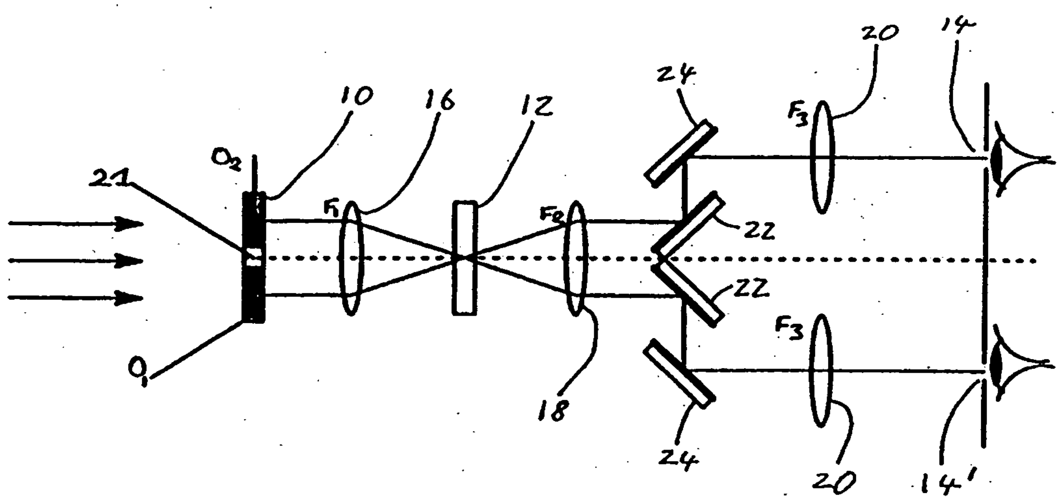

(57) Abstract

The 3–D image display uses a ferroelectric liquid crystal spatial light modulator FLC SLM (12) as a varifocal lens in an imaging system. The FLC SLM is programmed to perform as a Fresnel zone plate, FZP, with a plurality of different programmable focal lengths. The FLC SLM rapidly sequences through each of the focal lengths thereby forming, one after another, images of an object at different focal lengths. As long as the sequencing is sufficiently rapid, the human eye combines the sequence images and perceives the images as a single 3–D image. Additionally, the FLC SLM is programmed to incorporate a symmetry breaking filter in its performance as FZP so that only the positive (or negative) focal length of the FZP predominates in the centre of the image. As there are no parts requiring mechanical movement to ensure the creation of images at different focal lengths, the 3–D image system is particularly suited for use in a head–mounted display.

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3-D IMAGE DISPLAY

The present invention relates to a three dimensional (3-D) image display and in particular to a 3-D image display employing a ferroelectric liquid crystal spatial light modulator (FLC SLM). The present invention further relates to the use of such a 3-D image display in a head-mounted display. Separately, the present invention relates to a single FLC SLM arranged to perform as a Fresnel Zone Plate (FZP).

It has been known for some time that a variable focus mirror, lens or FZP could be used to generate a multi-planar 3-D image. For example, a mechanical vari-focus mirror based on driving a metallized stretched membrane with a loud speaker was described by Traub in Appl. Optics 6, 1085, 1967. More recently the use of a nematic liquid crystal as a programmable Fresnel Zone Plate was described by Tam et. al. in Appl. Optics, 31, 578, 1992. Such a system has the disadvantage though of having a switching speed which is too low to provide flicker-free multi-planar images.

On the other hand, ferroelectric liquid crystal used in a spatial light modulator can be patterned to perform as a FZP instead of a nematic liquid crystal. The ferroelectric liquid crystal switches between two states producing binary modulation of, for example, phase. As a consequence of binary modulation the FZP performs as a lens with both positive and negative focal lengths (other focal lengths are also formed but the fraction of light diffracted into these is negligibly small). These result in a pair of image planes and for this reason ferroelectric liquid crystals have not been considered for use in a variable focus FZP. The presence of a pair of image planes in a system which employs a ferroelectric liquid crystal modulator as a FZP can be overcome by using more than one liquid crystal to provide multi-level phase modulation but such a solution is both inconvenient and expensive.

In addition, health and safety problems have been encountered with the use of 3-D head-mounted displays. Such problems including general fatigue, headaches and difficulties in focusing following the use of a head-mounted 3-D display are believed to be associated with the fact that existing displays require the eyes to adjust vergence without any adjustment of accommodation.

The present invention seeks to overcome at least some of the problems mentioned above and seeks to provide a 3-D image display which employs a FLC SLM as a variable focus FZP. Furthermore, the present invention seeks to provide a 3-D head-mounted display employing a FLC SLM as a variable focus FZP which enables the eyes to perform naturally where vergence and accommodation are performed in a coupled manner.

The present invention provides a three dimensional image display comprising an input object generator, a ferroelectric liquid crystal spatial light modulator (FLC SLM), a viewing aperture, first optical means for directing an image from the input object generator to the FLC SLM, second optical means for directing a sequence of images from the FLC SLM to the viewing aperture and a control device for controlling the FLC SLM whereby the FLC SLM is adapted to perform as a Fresnel zone plate with a plurality of different focal lengths.

Preferably, a symmetry breaking phase filter is employed in combination with the spatial light modulator to significantly reduce the negative focal length image generated by the spatial light modulator without substantially affecting the positive focal length image. Alternatively, the symmetry breaking phase filter may be used to significantly reduce the positive focal length image without substantially affecting the negative focal length image. Ideally the spatial light modulator is arranged to incorporate the effect of a symmetry breaking phase filter. Additionally, the spatial light modulator may include crossed

polarising filters.

Ideally, the spatial light modulator is arranged to cycle sequentially through all of the plurality of different focal lengths at least twenty-five times per second.

In a further aspect the present invention provides a head-mounted display comprising an object generation device for generating a pair of substantially identical objects and at least one ferroelectric liquid crystal spatial light modulator adapted to perform as a Fresnel Zone Plate with a plurality of different focal lengths and optical means for directing light from the object generation device to the ferroelectric liquid crystal spatial light modulator and further optical means for directing light modulated by the spatial light modulator with the plurality of focal lengths to first and second viewing apertures.

With the head-mounted display the first and second viewing apertures are provided for the left and right eyes. In this way the eyes are required to perform both vergence and accommodation simultaneously.

By way of example, the object generation device is in the form of a spatial light modulator which generates two substantially identical objects adjacent one another with a blank space between. A single spatial light modulator arranged to perform as a variable focus Fresnel zone plate can be employed for generating pairs of images each pair at a different focal length. Alternatively, the head mounted display may include two ferroelectric liquid crystal spatial light modulators for separately generating pairs of objects.

In addition, although two orthogonal identical cylindrical lenses provide the same performance as a spherical lens it is accepted that the superposition of two orthogonal one dimensional FZPs does not provide the same performance as a circularly symmetric FZP. Therefore, conventionally, each pixel of a SLM is separately driven to provide circularly symmetric FZP performance, apart from pixellation.

The present invention separately provides a single SLM which performs as a substantially circularly symmetric FZP, the SLM is patterned with the superposition of two orthogonal one dimensional FZP patterns. In this way the single SLM can function as a circularly symmetric FZP with a significant reduction in the number of bits of information necessary to drive the SLM in comparison to SLMs conventionally patterned to provide circularly symmetric (apart from pixellation) FZP performance (to be referred to as two dimensional FZP). Indeed, the number of bits of information required to drive the SLM is reduced from N^2 to 2N or less (where N is the number of pixels in one dimension in a square SLM). This reduction in the necessary number of bits affords a significant improvement in terms of not only speed of operation but also simplicity in the drive circuit design, reduction in the necessary information storage and transfer and overall cost. This is an example of various schemes of pixellation and patterning which can take advantage of the reduced information requirements to drive a device required to give circularly symmetric performance.

The overall performance of the SLM as a FZP can be further improved by combining a fixed phase filter pattern to suppress the negative or positive focal length.

Embodiments of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figures 1a and 1b are three dimensional graphical representations of intensity distribution in the focal plane of a two dimensional FZP and a pair of orthogonal one dimensional FZPs respectively, both implemented using a ferroelectric liquid crystal spatial light modulator;

Figure 2 is a schematic diagram of an optical arrangement for producing images of an object at variable positions with respect to a viewing aperture; and

Figure 3 is a schematic diagram of a stereoscopic 3-D image display employing a FLC SLM for use in a head-mounted display.

In the context of the following discussion reference herein to a SLM is intended as reference to a ferroelectric liquid crystal spatial light modulator (FLC SLM), unless otherwise indicated. It is implicit that the FLC SLM and polarizers are configured to give phase-only modulation unless otherwise stated. In its simplest form the FLC SLM consists of a slab of ferroelectric liquid crystal defining an array of individually electronically addressable pixels sandwiched between two optically transparent electrodes. Each pixel behaves as a uniaxial crystal with an optic axis whose angular orientation may be controllably altered. Indeed the pixels can be operated as retardation plates providing two discrete states of modulation. A detailed discussion of the theory of spatial light modulators employing ferroelectric liquid crystal material may be found in WO 95/15513.

The FLC SLM described above may be used to function as a Fresnel Zone Plate (FZP). In order to do so the FLC SLM is arranged so that the phase modulation of each pixel is quantised to either 0 or QQ radians with the selected orientation of each pixel being determined in dependence on the desired focal length of the FZP. Where different focal lengths are desired the liquid crystal orientation of each of the pixels is separately determined for each focal length and the orientation may alter for different focal lengths. For each focal length there is therefore a different set of pixel states and the focal length of the FLC SLM is altered by changing the individual liquid crystal orientations of the pixels in accordance with the relevant set of pixel states. In this way the FLC SLM is capable of focusing an image at different predetermined focal lengths.

In order to generate a three dimensional image, the FLC SLM must be capable of cycling sufficiently quickly through different focal lengths to produce an image which is flicker-free. It will of course be

understood that reference to flicker-free images is intended as reference to images cycled at a faster rate than a human is capable of discriminating, in practice this requires a rate of at least 25 images per second. In order to achieve the perception of a three dimensional image the set of different focal lengths must be treated as a single image packet. Therefore, the entire packet or set of different focal lengths must be sequentially cycled through at least 25 times per second. Currently available FLC SLMs are capable of being refreshed more than 1000 times per second. This means in turn that more than forty different focal length images may be generated whilst still achieving flicker-free operation.

The FLC SLM patterned as a FZP has both a negative and positive focal length. Thus images are created in two planes simultaneously. To suppress one of the images a symmetry breaking phase filter is employed. The phase filter consists of an array of pixels each of which generates a phase shift of either 0 or QQ/2 radians. The phase shift of individual pixels is fixed so that the image associated with the negative (positive) focal length is caused to be blurred and displaced to the edges of the image frame whereas the image associated with the positive (negative) focal length is left substantially unaltered. The phase shift of individual pixels in the phase filter and the matching pixel states in the FLC SLM can be determined using an iterative optimisation algorithm (e.g. direct binary search) such as the procedure described by Neil and Paige in IEE Conf. Pub. 379, 85, 1993.

In addition, the attenuation which normally accompanies the use of a FLC SLM may be reduced significantly by incorporation of a quarter wave plate as described in WO 95/15513.

In Figure 1a a graphical representation of the intensity distribution in the focal plane of a FLC SLM arranged as a two dimensional FZP and illuminated with a plane wave is shown. To significantly reduce the number of bits of information needed to pattern the FLC SLM to

perform in a way similar to a two dimensional FZP, two orthogonal one dimensional FZP patterns can be superposed. The resultant performance of an adapted FLC SLM patterned in this way is shown in Figure 1b. As can be seen the performance of the adapted FLC SLM is substantially the same as that of the FLC SLM of Figure 1a albeit with a small amount of aberration and a reduction of about 50% in light intensity at the focus. These disadvantages though are outweighed by the advantages of the reduction in the number of bits of information from N^2 to 2N or less, for a square FLC SLM having N pixels along one side. This reduction in the number of bits affords consequent benefits in terms of the speed of operation, the simplicity of the drive circuit, the reduction in information storage and transfer and the overall cost. Furthermore, the image associated with the negative (positive) focal length can be suppressed by adaptation of the symmetry breaking phase filter and the aberration in the form of the side lobes seen in Figure 1b can also be suppressed by further optimisation of design.

An optical arrangement for producing three dimensional images is shown in Figure 2. With this arrangement an image is focused at different positions with reference to the viewing aperture 14. The arrangement consists of an object generator 10 which presents the light which is to be focused at different positions. The object generator 10 may be in the form of a first SLM. The objector generator 10 need not be a ferroelectric liquid crystal spatial light modulator, other types of spatial light modulator may be employed and the SLM is preferably intensity modulated. Of course alternative optical means may be used to produce the object which will be the subject of variable focusing. A variable focus SLM 12 is provided between the object generator 10 and the viewing aperture 14 with first and second lenses 16 and 18 provided between the first SLM 10 and the variable focus SLM 12 and between the variable focus SLM 12 and the first image plane of the object respectively. A third lens 20

is provided to place the image generated by the foregoing system at an appropriate distance for viewing from the viewing aperture 14. The first SLM 10 performs as an amplitude modulator and the variable focus SLM 12 acts as a phase modulator and is controlled by a control device (not shown) so that the SLM performs as a variable focal length FZP, as described earlier. Although both SLM's are shown in transmission mode, by incorporation of additional optics SLM's operating in reflection mode (e.g. Silicon back-plane FLC SLM) can be utilized. The variable focus SLM 12 may incorporate a symmetry breaking filter through suitable adjustment of individual pixels of the SLM or a separate symmetry breaking phase filter (not shown) may be provided adjacent to the variable focus SLM 12 which incorporates matching altered pixel states.

The two SLMs 10, 12 are synchronised to create a sequence of flicker-free images $i_1, i_2, i_3, \ldots i_n$ in depth planes $d_1, d_2, d_3, \ldots d_n$. As long as the complete sequence of images are cycled through faster than 25 times a second then the images are perceived through the viewing aperture as a single 3-D image. The image I is shown in Figure 2 for which the SLM 12 has a focal length = ∞.

As mentioned earlier the image to be focused at different focal lengths is generated using a FLC SLM this enables a grey scale to be introduced in the image through the introduction of temporal dither. Alternatively, a colour image can be produced by employing different coloured LEDs, for example, and sequentially cycling through each of the colours as well as the different focal lengths. Suitable correction for the wavelength dependence of the FLC SLM is synchronously incorporated as necessary. Temporal dither and colour can be combined to produce a shaded colour image.

In order to provide a stereoscopic display the optical arrangement described above may be duplicated to provide a separate viewing aperture for each eye. Such an arrangement is shown in Figure 3.

The object generator 10, which again may be a SLM, produces two substantially identical objects O_1 and O_2 corresponding to left and right eye objects respectively with a central blank zone 21. The light is then transmitted through a first lens 16, which is common to both images, onto the variable focus SLM 12. As mentioned earlier the variable focus SLM may have a symmetry breaking phase filter and/or may be operated in reflection mode. The two output images from the variable focus SLM 12 are then collimated through a second lens 18 and directed to respective viewing apertures 14 and 14' for the right and left eyes respectively, via first and second mirrors 22, 24 and third lenses 20. Although a single SLM is shown functioning as the variable focus Fresnel zone plate for both the left and right eye images, it will be appreciated that separate SLMs may be employed for each of the eye images. Similarly the single object generating SLM may be replaced by a pair of SLM's. The binocular display system is then essentially the arrangement shown in Figure 2 duplicated to create a viewing channel for each eye.

To design a head-mounted display in which a person with defective sight can wear their spectacles will increase weight and bulk. An alternative is provided by the head-mounted display incorporating the FLC SLM as a variable focus FZP by customizing the SLM pattern via the software to build the correction into the FZP normally supplied by the viewer's spectacles. If the correction to each eye is different then either a display with two variable focus SLM's is required or else the left and right eye images would need to be time multiplexed. If the correction was other than for a reduction in the ability to accommodate, the symmetry of the correction would preclude the use of the previously mentioned scheme which reduced the number of bits of information required to drive the SLM.

The optical arrangement shown in Figure 3 can be employed in a head-mounted 3-D display. As is usual with a head-mounted display each eye is presented with one of a pair of stereoscopic images which the

eyes, by varying their vergence, fuse to give the appearance of an image in some depth plane in a 3-D scene. The images are of course located in a fixed plane. By incorporating the FLC SLM as a variable focus FZP, the fused image can be placed in its appropriate depth plane. This has the advantage that the eyes are being called on to perform as they normally do when they normally view a 3-D scene - simultaneous adjustment of vergence and accommodation is taking place. It is believed that some of the health and safety problems currently encountered with head-mounted displays may be at least reduced and possibly avoided employing the FLC SLM as a variable focus FZP as the eyes are being required to perform their usual function instead of being required only to perform vergence without accommodation as with known head-mounted displays.

It will of course be appreciated that the arrangement and type of optical elements shown in the Figures may be altered whilst still providing a 3-D image display with a FLC SLM patterned to perform as a variable focus FZP.

CLAIMS

1 A three dimensional image display comprising an input object generator, a ferroelectric liquid crystal spatial light modulator (FLC SLM), a viewing aperture, first optical means for directing an image from the input object generator to the FLC SLM, second optical means for directing a sequence of images from the FLC SLM to the viewing aperture and a control device for controlling the FLC SLM whereby the FLC SLM is adapted to perform as a Fresnel zone plate with a plurality of different focal lengths.

2 A three dimensional image display as claimed in claim 1, further including a symmetry breaking filter for reducing one of either the positive or negative focal length image directed to the viewing aperture by the second optical means without substantially affecting the other of the positive or negative focal length image directed to the viewing aperture.

3 A three dimensional image display as claimed in claim 2, wherein the control device adapts the FLC SLM to perform as a Fresnel zone plate incorporating the symmetry breaking filter.

4 A three dimensional image display as claimed in any one of the preceding claims, wherein there is further provided crossed polarising filters and the FLC SLM is a phase modulated SLM.

5 A three dimensional image display as claimed in any one of the preceding claims, wherein the control device includes a timing device whereby the FLC SLM is adapted to cycle sequentially through a plurality of different focal lengths at least twenty-five times per second.

6 A three dimensional image display as claimed in any one of the preceding claims, wherein the object generation device is an intensity modulated SLM.

7 A spatial light modulator patterned with the superposition of two orthogonal one dimensional Fresnel zone plate patterns whereby the

spatial light modulator performs substantially as a circularly symmetric Fresnel zone plate.

8 A three dimensional image display as claimed in any one of claims 1 to 6, wherein the FLC SLM is patterned in accordance with the spatial light modulator of claim 7.

9 A head-mounted display comprising a double image object generator for generating a pair of substantially identical objects; at least one ferroelectric liquid crystal spatial light modulator (FLC SLM) adapted to perform as a Fresnel zone plate with a plurality of different focal lengths; first optical means for directing light from the double image object generator to the at least one FLC SLM; first and second viewing apertures; and further optical means for directing light modulated by the at least one FLC SLM to the first and second viewing apertures.

10 A head mounted display as claimed in claim 9, wherein there is further provided at least one symmetry breaking filter for reducing one of either the positive or negative focal length images directed to the first and second viewing apertures without substantially affecting the other of the positive or negative focal length images directed to the first and second viewing apertures.

11 A head-mounted display as claimed in either of claims 9 or 10, wherein two FLC SLMs are provided to modulate respective images generated by the double image object generator.

12 A head mounted display as claimed in either of claims 9 or 10, wherein a single FLC SLM is provided to modulate images of the pairs of objects generated by the double image object generator and the further optical means includes reflecting devices for directing the modulated images from the FLC SLM to one or other of the first and second viewing apertures.

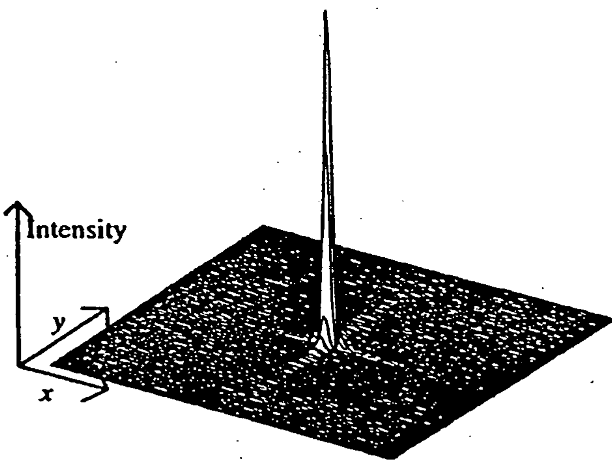

FIGURE 1a

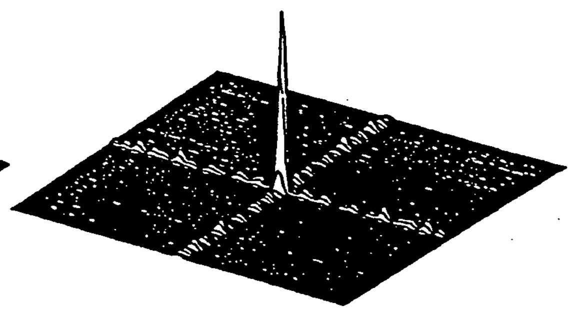

FIGURE 1b

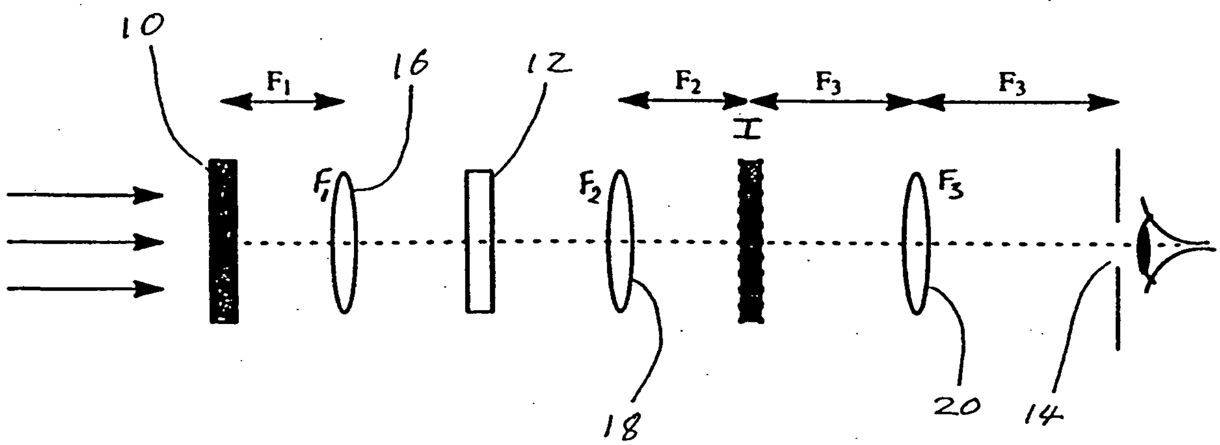

FIGURE 2

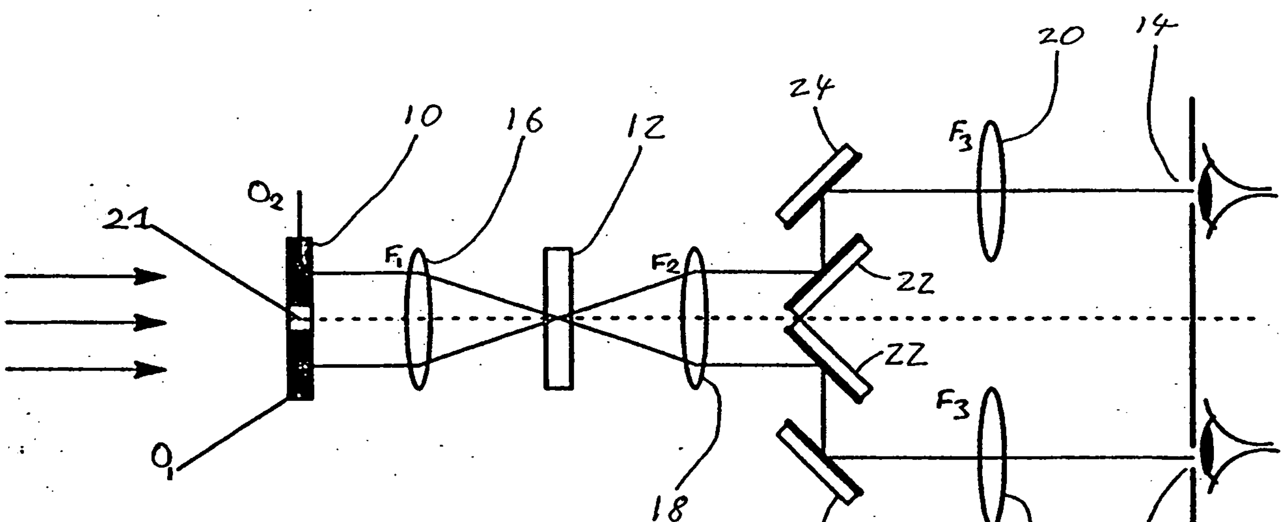

FIGURE 3

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B27/22 G02B27/01 G02F1/29

According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 497 254 A (AMAKO JUN ET AL) 5 March 1996 see column 13, line 1 - column 15, line 37; figures 18-22 ---	1,4-9
A	TAM E C ET AL: "SPATIAL-LIGHT-MODULATOR-BASED ELECTRO-OPTICAL IMAGING SYSTEM" APPLIED OPTICS, vol. 31, no. 5, 10 February 1992, pages 578-580, XP000247290 cited in the application ---	1-3,6,7, 9,10
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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